

Studying the Stars on Earth: Astrophysics on Intense Lasers

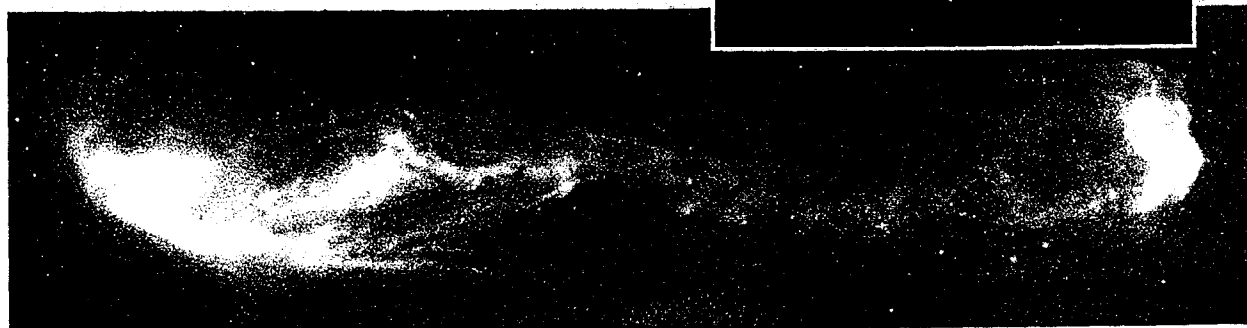
Bruce A. Remington

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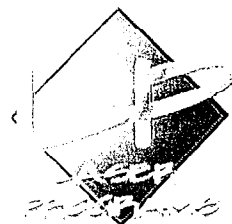
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March 1999

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One of the biggest problems facing astrophysicists is our inability to study the stars up close. The need to test our physics models and theories is frustrated by our lack of an appropriate laboratory. But a solution has appeared in the unlikely realm of large-scale laser research. In addition to a host of other types of science research, Lawrence Livermore National Laboratory in Livermore, California, is now performing significant astrophysics experiments on its huge Nova laser facility, and a similar effort has started at the Gekko laser facility at Osaka University in Japan.

The Nova laser is one of a handful of large lasers around the world engaged in the study of inertial confinement fusion. By shooting many powerful laser beams onto a spherical capsule containing hydrogen and its isotopes—essentially the same stuff found in the center of stars—an inertial confinement fusion experiment compresses the capsule until the hydrogen atoms within fuse, or merge, which releases energy in a burst of neutrons. The pursuit of this energy for various applications is the original motivator of the Livermore laser facility, but recently scientists have realized its potential for the study of astrophysics.

The Nova laser appears to be particularly well suited for studying the hydrodynamics of core-collapse supernovae, stars that suddenly burst into extreme brilliance as a result of exploding from the inside out. In fact, we have no other way to create such starry conditions on Earth. The fluid-like motion (or hydrodynamics) of the star's gases is a topic of great interest for astrophysicists. In the recent supernova of 1987 (SN1987A), a result of the explosion of the blue super-giant star Sanduleak located in the nearby Large Magellanic Cloud galaxy,¹ there is convincing evidence that the star's core penetrated outward to the surface much sooner than expected. Hydrodynamic instabilities are suspected as the cause of this stellar surprise. During a Nova laser experiment, the hydrodynamics within a target can be made to closely resemble conditions within a supernova like SN1987A, in particular the evolution of the hydrodynamic instabilities suspected in SN1987A. Astrophysics experiments on the Nova laser so far confirm the strong similarity between supernovae and laser experiments, opening up a new arena: the laboratory study of supernova hydrodynamics.

We designed the first Nova laser astrophysics experiments (in collaboration with researchers from the University of Arizona, University of Colorado, University of Michigan, and CEA-Saclay in France) to emulate a supernova's most important hydrodynamic features. Figure 1a shows the growth of perturbations (counter-

clockwise through four time periods) in a two-dimensional (2D) computer simulation of SN1987A,² whose boundary is propelled outward by the shock from the explosion in the center. These perturbations are caused by the star's denser inner layers being decelerated by the overlying lower-density material as the core rushes outward and mixes with the surrounding envelope. This mixing is caused by what is known as the Rayleigh–Taylor instability, which is a key process in the hydrodynamics of supernovae.

Figure 1b shows laboratory data radiograph from the Nova laser experiment³ designed to reproduce the conditions in Figure 1a. Although the width of the star is 40 million miles while that of the miniature Nova laser “star” is only about 400 micrometers (just under half a millimeter), the radiograph shows that the same hydrodynamic action occurs in both. Likewise, the same mixing that happens over two or three hours in the supernova takes place in less than 50 billionths of a second in the Nova laser experiment. In addition to emulating the effect accurately, the shock hydrodynamics experiment also improved our understanding by showing that the tips of the 3D mixing spikes grow significantly faster than would be predicted in a standard 2D computer simulation. The ability to continuously improve computer models by comparison to real experimental data is crucial to advancing astrophysics, as it is in other areas of science that rely on computer simulations.

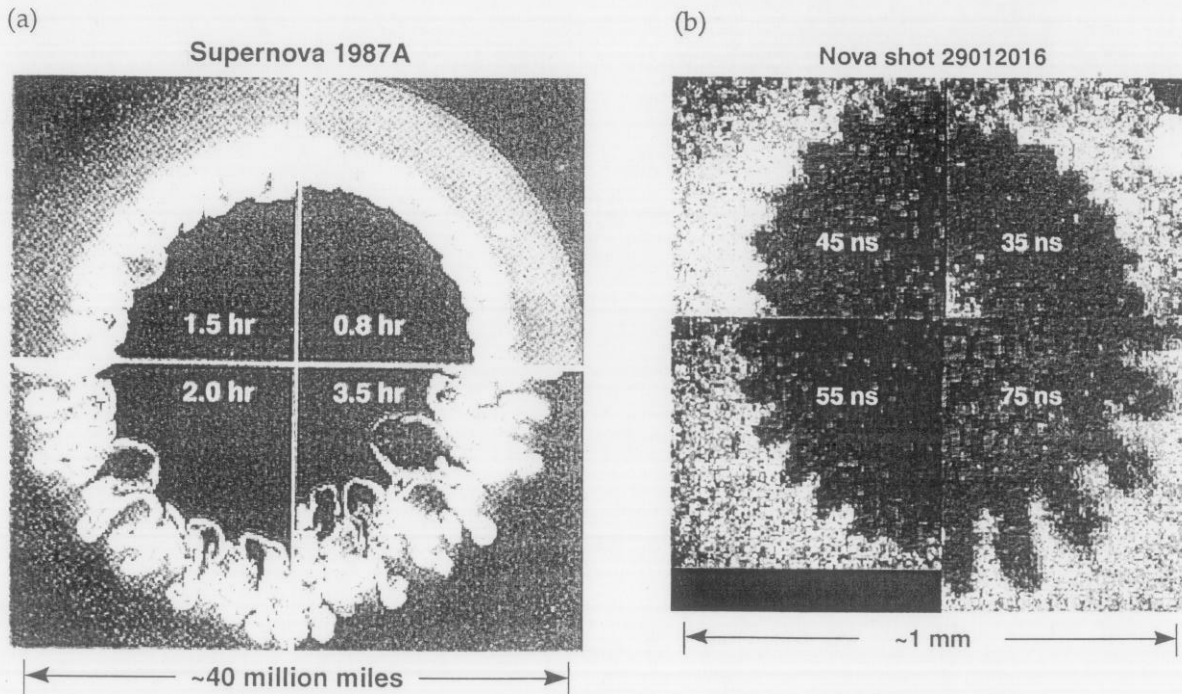


Figure 1. (a) The simulated growth of perturbations (counter-clockwise through four time periods) in the outer regions of the star as it explodes into prominence as Supernova 1987A (Ref. 2). (b) Nova laser experimental radiographs showing remarkable supernova-like mixing features (Ref. 3).

Some of our work on the Nova laser addresses not just the interpretation of past supernova explosions but a spectacular collision poised to begin beyond our own galaxy. Astrophysicists anxiously await the time when the blast wave and expanding ejecta (the star's ejected material) created by the explosion of SN1987A will impact its circumstellar nebular ring (the ring that surrounds the star). Figure 2a shows a photo taken by the Hubble Telescope in 1994, seven years after the star's initial explosion. In the photo, the ejecta form the yellow central dot, and the circumstellar nebula is shown as the inner yellow ring. (The outer rings, which are not well understood, are not addressed in the experiments we are currently conducting.)

The imminent impact of the supernova blast wave with the inner ring will show us vividly how the ring responds to violent shock heating. Our ability to interpret what happens from this impact depends heavily on how well we understand strong-shock plasma hydrodynamics. The ring is predicted to literally light up; the bright "sparkles" we expect to see are due to the shock wave moving outward into the circumstellar ring, impacting "clumps" of material within the ring. The blast wave impact has just started (as of 1999), with one such sparkle already being observed by astrophysicists.⁴ The reverse shock, which lies just inside the leading edge of the ejecta, is about three fourths of the way to the ring at this time.

Scientists have developed astrophysics computer models to predict the outcome of this impact, but experiments on the Nova laser allow us to test the essential ingredients of these models prior to the full impact.⁵ In Figure 2b, a streaked image shows the laser-target ejecta (the reverse shock) in a Nova experiment preceded by the blast wave (the

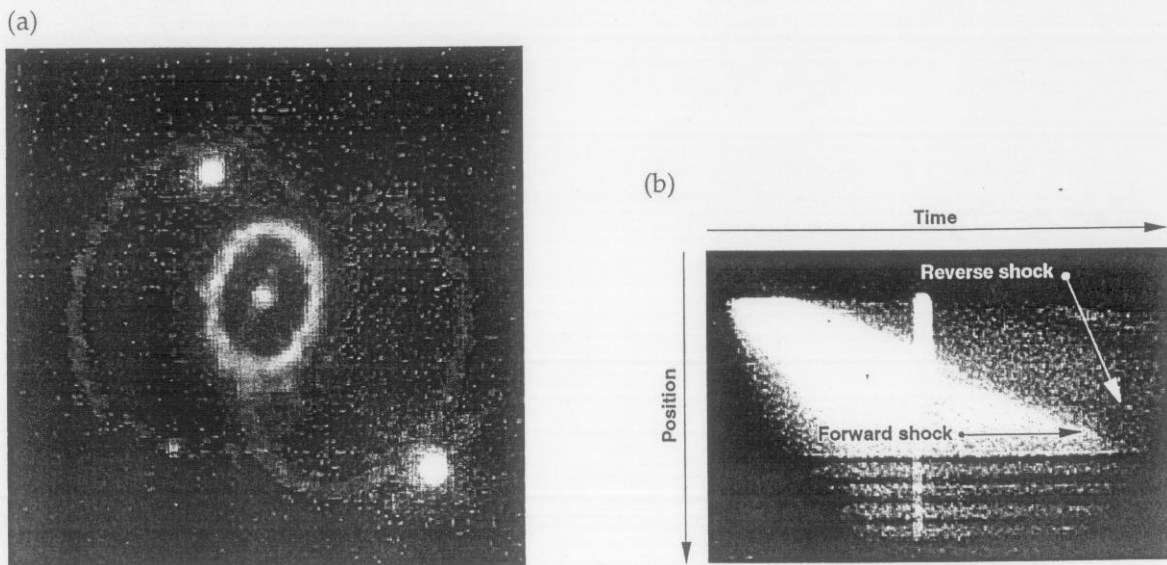


Figure 2. (a) Hubble Telescope image of Supernova 1987A in February 1994, seven years after the star's explosion. In 1999, the shock wave from the explosion is just now reaching the nebular ring. (b) A raw, streaked image of the forward shock (or blast wave) and reverse shock (ejecta) in a Nova laser experiment (Ref. 5).

forward shock). The behavior of these shock waves is very similar to that of blast waves from exploding stars moving through the surrounding ambient medium; the scales are billions of times different, but the hydrodynamics remains identical. By comparing such experiments against the predicted evolution in supernovae, we can increase our confidence in the interpretation of the data that we will see when the nebular impact finally occurs in full force in Supernova 1987A.

We are also developing laser experiments to study the radiative hydrodynamics that occurs in astrophysical jets, where newly forming stars eject material in the form of jets traveling at many times the speed of sound (surpassing the speed of sound is what creates a shock wave). Astrophysical jets, such as the well known Herbig-Haro object HH47 shown in Figure 3,⁶ have emerged as galactic laboratories for the study of radiative hydrodynamics. These super-fast jets are thought to be strongly radiative, where radiative emissions carry heat away and thus cool the jet plasma, thereby considerably changing the jet's overall structure and hydrodynamics. Modeling this type of hydrodynamics is tricky, and laboratory benchmark data would be highly beneficial to astrophysicists. In collaboration with the University of Maryland and Osaka University, Japan, we are therefore developing experiments on the Nova laser and Osaka University's Gekko laser to study such radiative jets in our own laser-produced reproductions.⁷

In the first of these experiments, we used the laser to form a hot, radiative jet launched at a speed of 700 km/s (about 2 million miles per hour). Figures 4a and 4b show side-by-side color-enhanced photographs of the hot jet in x-ray emission, taken on the Nova laser, and as an x-ray shadow, taken on the Gekko laser. Both jets exhibit features similar to a typical galactic jet like the one in Figure 3 (super-fast and radiatively cooled). This effectively allows us to study aspects of the Herbig-Haro jets up close and in great detail. In fact, in simulations that do not include these radiation effects, the jet remains about ten times hotter, ten times broader, and ten times less dense than in the fully radiative simulation of our jet, quite a large margin of error.

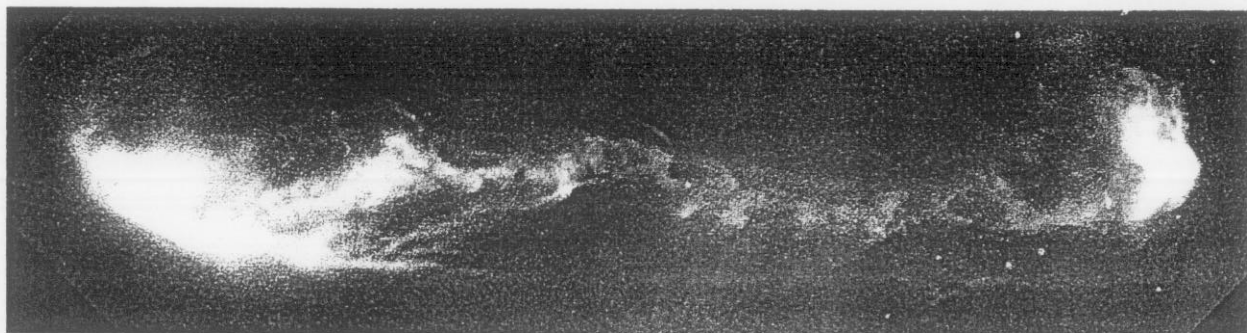


Figure 3. The well known Herbig-Haro object HH47, a radiative jet in space (Ref. 6).

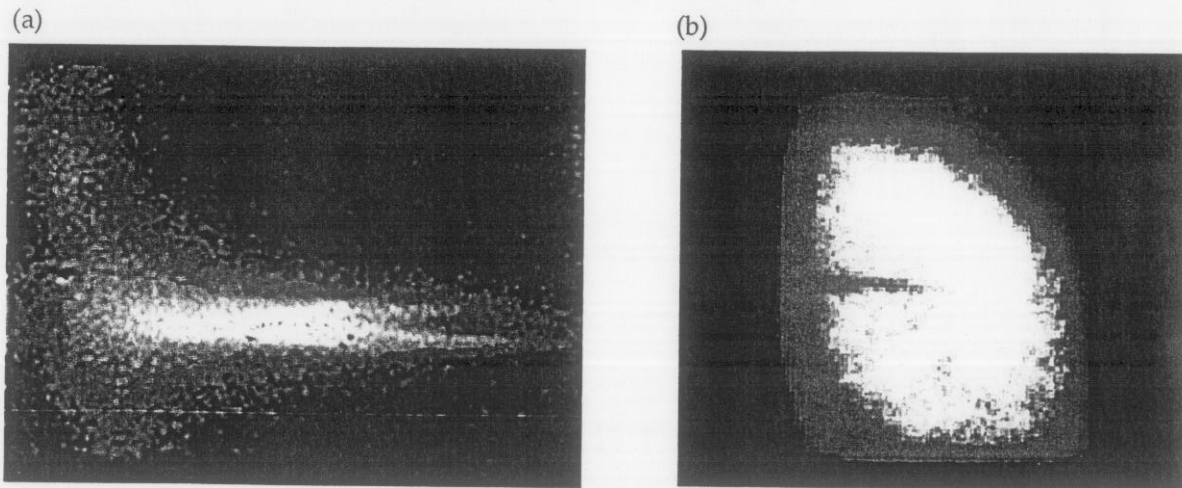


Figure 4. Radiative jets formed in a Nova laser experiment, in emission (a) and in x-ray absorption in the Gekko laser experiment (b), showing the same features as their galactic inspiration (Ref. 7).

Our experiments on the Nova and Gekko lasers so far encourage us that our astrophysics work is already leading to a better understanding of the hydrodynamics of supernovae and astrophysical jets. The ability of large inertial confinement fusion lasers to recreate star-like conditions in the laboratory greatly improves our understanding of the heavens; for the first time in our history, we can study the stars up close on Earth.

Acknowledgements

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